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Title: Detecting neutrons, from ultra-hot to ultra-cold energies

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# Detecting Neutrons

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*From ultra-hot to ultra-cold energies*

Zhehui (Jeph) Wang

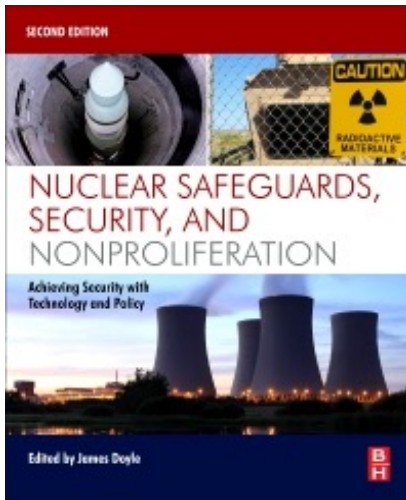
*P-4, Los Alamos National Laboratory  
(May 27, 2021)*

# Outline

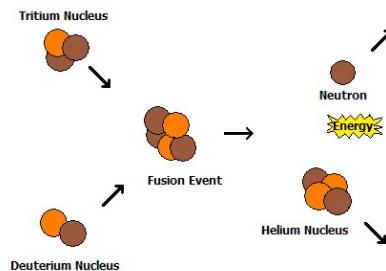
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- **Motivations & Background**
  - Applied science: Threat Reduction/HS, Material discovery, Fusion energy, ...
  - Discovery science: Nuclear Physics, Physics beyond standard model, QIS, ...
- **Detector development**
  - Multilayer B10 thin film detectors
  - UCN detectors
  - SIFaN (fast neutron tracking)
- **Summary**

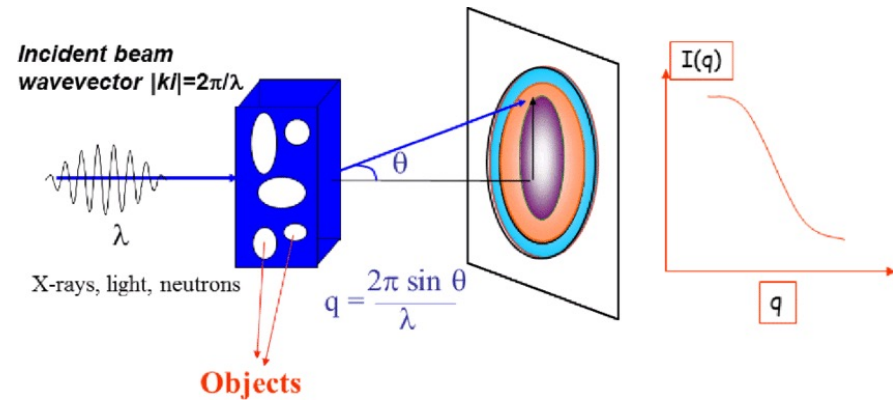
# Neutron detection in Applied Science



Fission neutrons

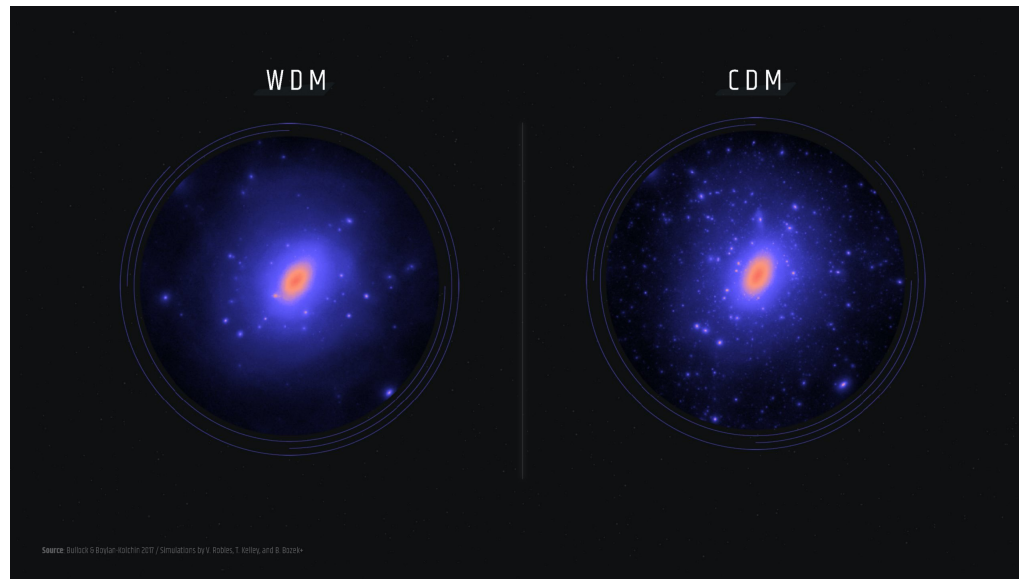


Fusion neutrons



Thermal neutrons  
(0.18 nm)

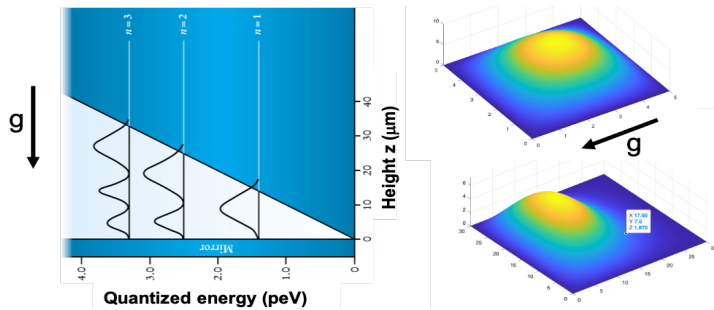
# Neutron detection & dark matter mystery



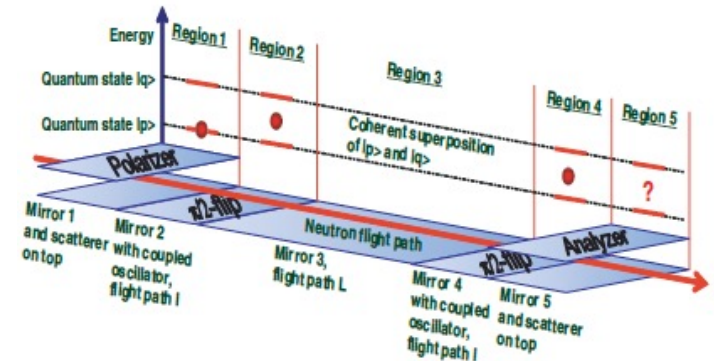
$$E_x > 2.9 \times 10^{-21} \text{ eV}$$

E. O. Nadler et al, <https://arxiv.org/abs/2008.00022>

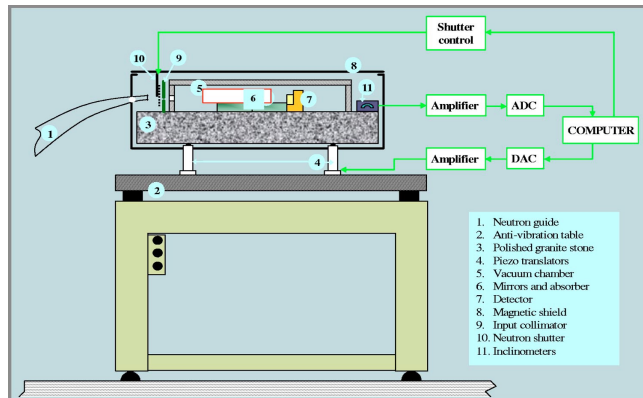
# Neutron quantum states as a ultrahigh sensitive probe



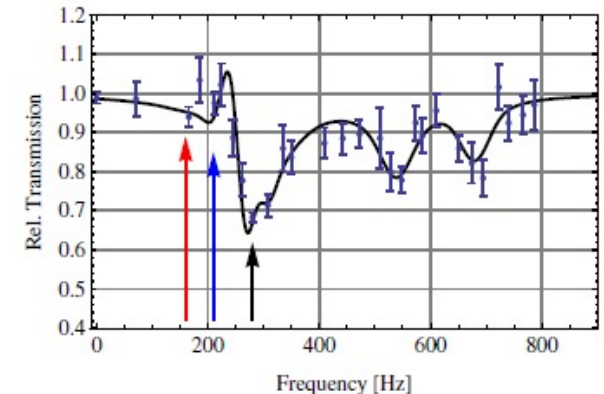
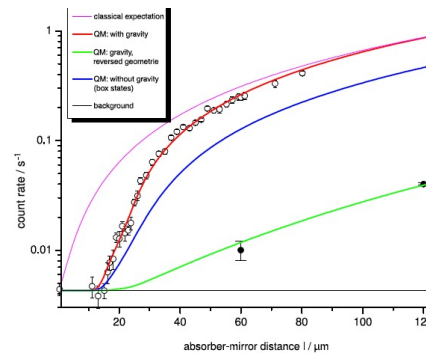
$\sim 10^{-12}$  eV



Abele et al (2010)



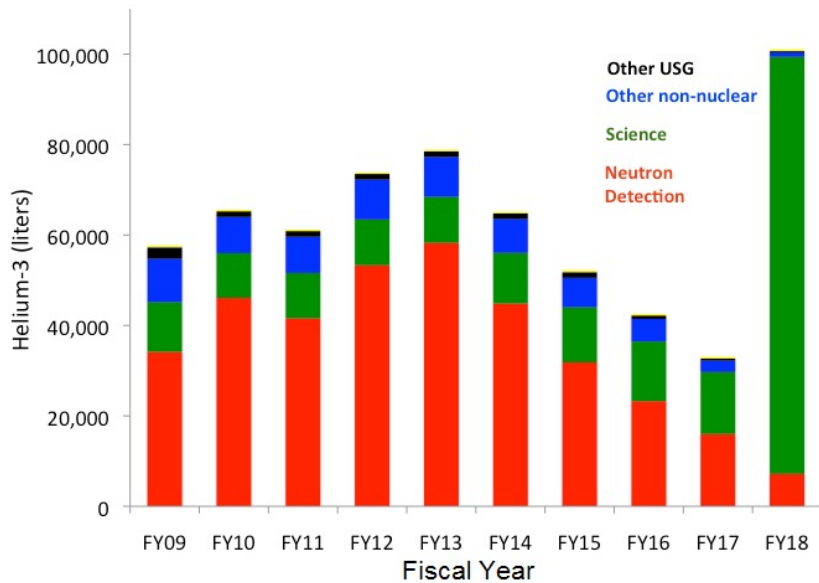
Nesvizhevsky et al. PRD 67 (2003) 102002



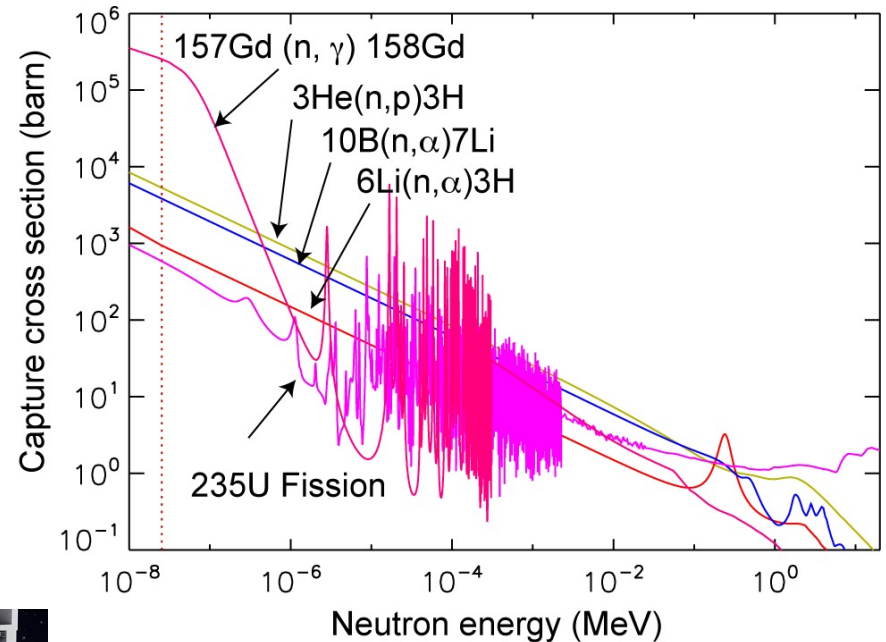
Jenke et al (2014)

$\sim 10^{-15}$  eV (Th:  $10^{-21}$  eV)

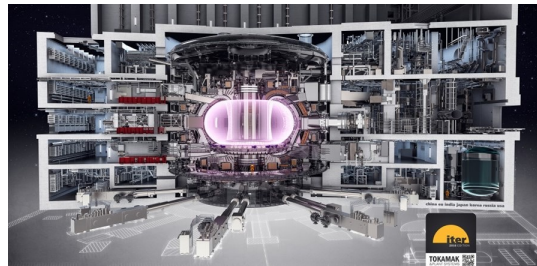
# Our approach driven by $^3\text{He}$ shortage problem



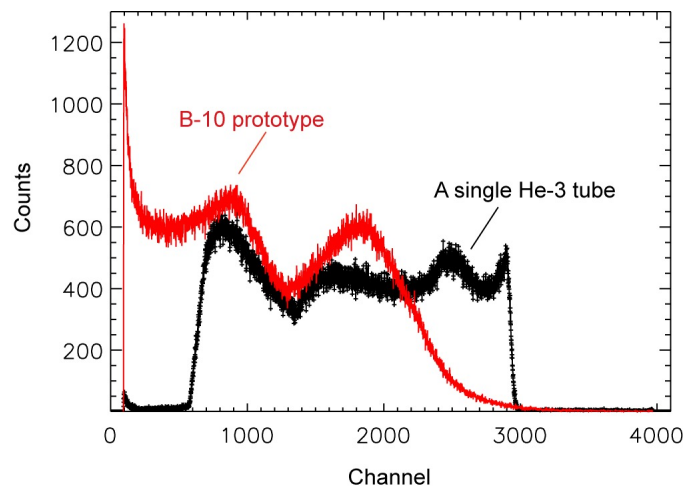
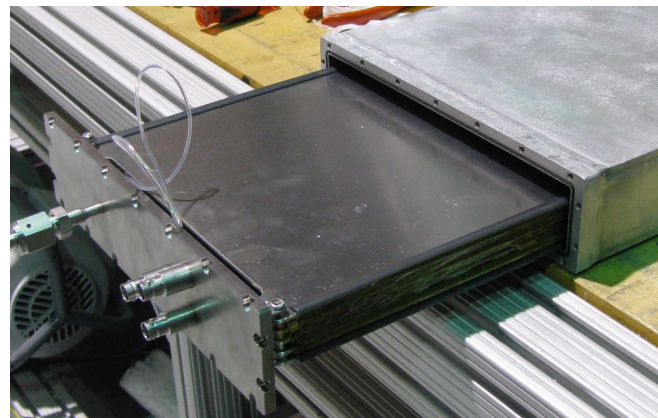
D. A. Shea & D. Morgan, *CRS Reort* (2010)



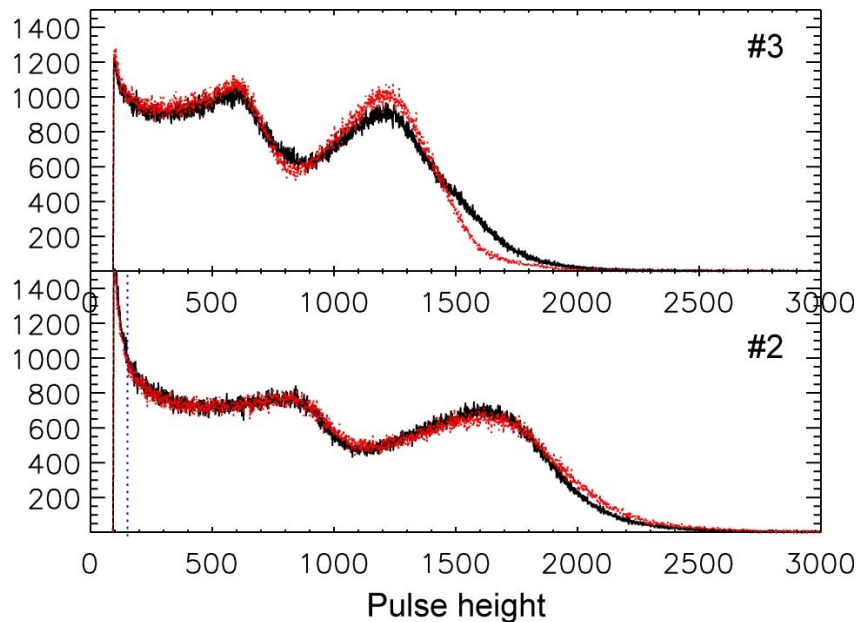
$$\sigma(^{10}\text{B}) \sim 72\% \sigma(^3\text{He})$$



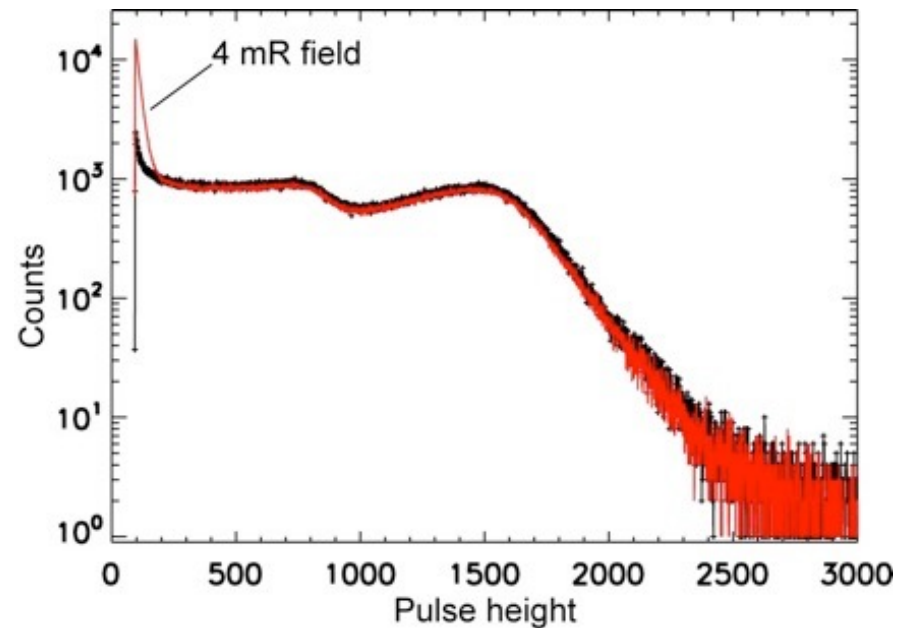
# The $^{10}\text{B}$ powder neutron detectors



## Performance (B): stability & $\gamma$ -sensitivity

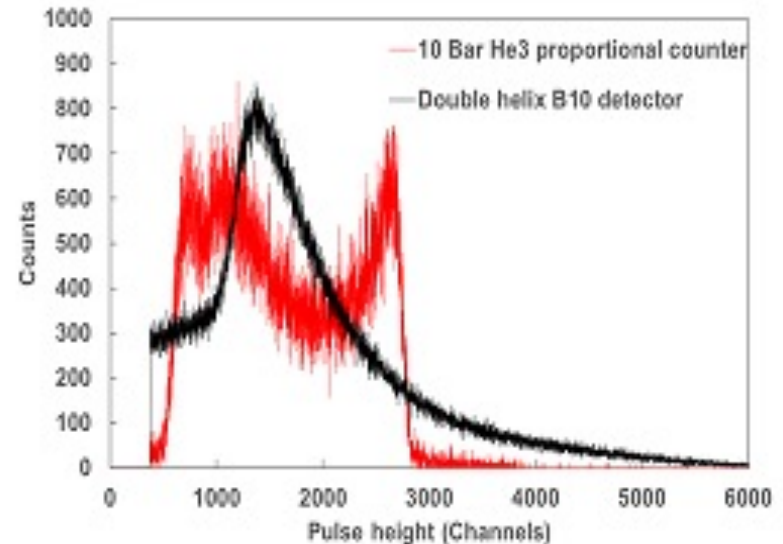


~ 18 months apart



~ 10% efficiency loss

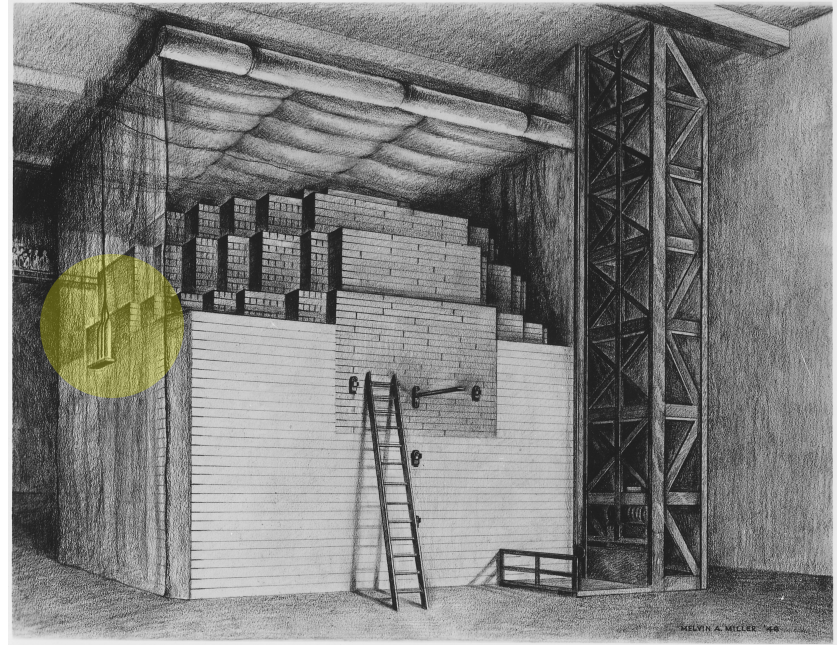
# AWE/UK validation of efficiency & $\gamma$ -insensitivity



Detector	$\epsilon_{int n}$ (%)	$GARRn$ @ 20 mR/hr
LANL $^{10}\text{B}$	$4.94 \pm 0.23$	$1.00 \pm 0.01$
$^3\text{He}$ : 10 bar	$11.09 \pm 0.42$	$1.01 \pm 0.05$
$^3\text{He}$ : 2 bar (equiv.)	$5.98 \pm 0.23$	$1.01 \pm 0.05$

# Optical/wave-like neutron known since Fermi

*On Dec. 2, 1942, Fermi & his team achieved sustained chain reaction, and the first fission reactor. Key elements: fuel, neutron moderator, control rod, neutron detector, and radioactivity detector.*



**Chicago Pile-1 (CP-1)**

# Ultracold → Total reflection from surfaces

Material:	$V_F^{[8]}$	$v_C^{[9]}$	$\eta (10^{-4})^{[9]}$
Beryllium	252 neV	6.89 m/s	2.0-8.5
BeO	261 neV	6.99 m/s	
Nickel	252 neV	6.84 m/s	5.1
Diamond	304 neV	7.65 m/s	
Graphite	180 neV	5.47 m/s	
Iron	210 neV	6.10 m/s	1.7-28
Copper	168 neV	5.66 m/s	2.1-16
Aluminium	54 neV	3.24 m/s	2.9-10

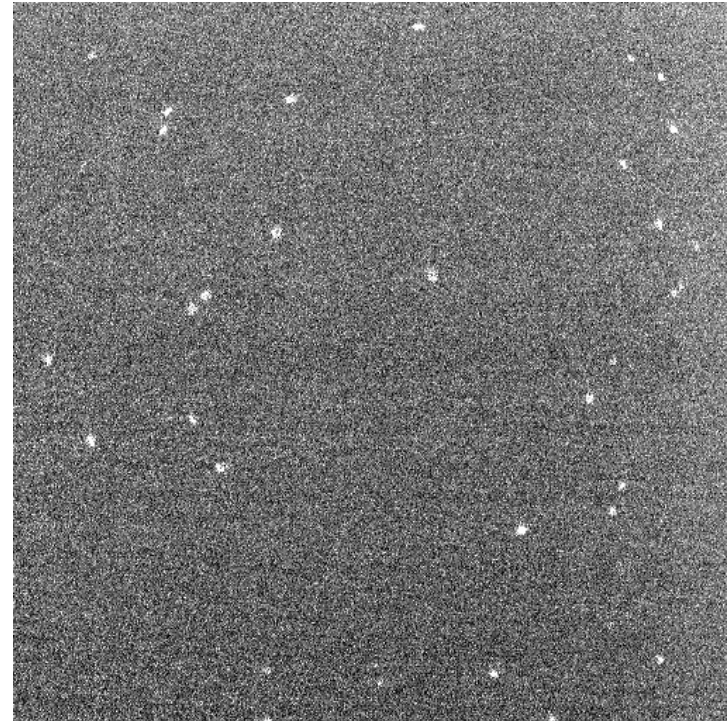
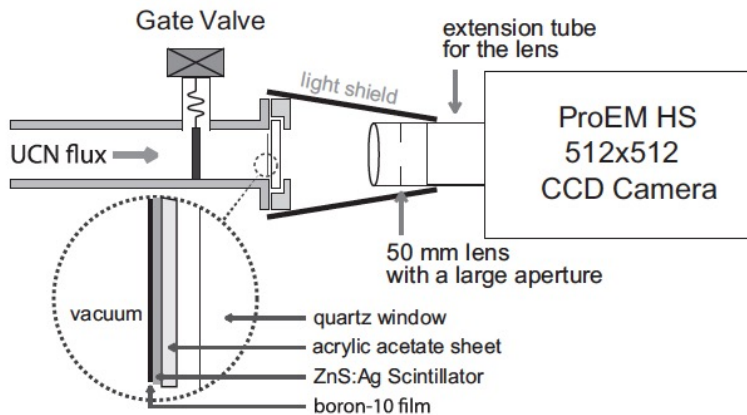


Fermi potential

$$^{58}\text{Ni} = 335 \text{ neV}$$

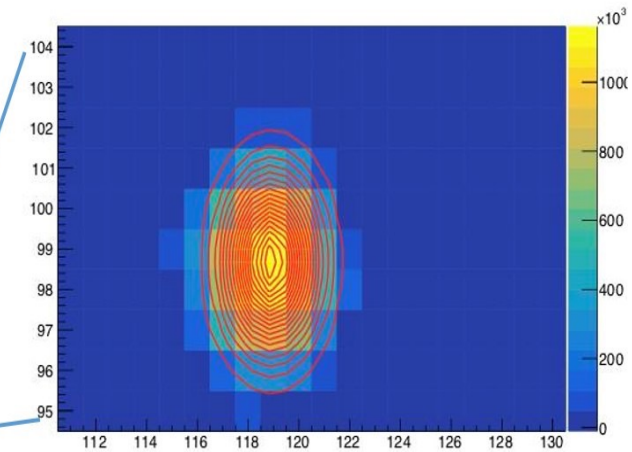
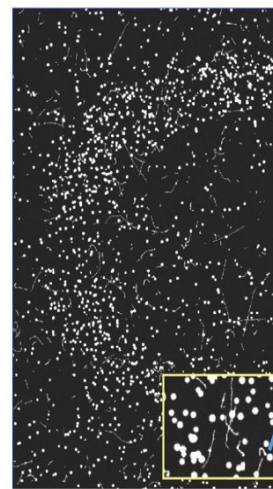
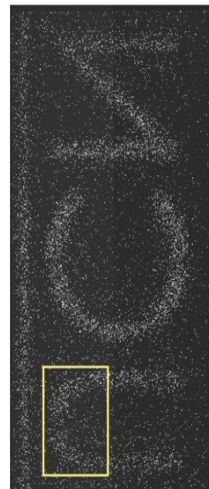
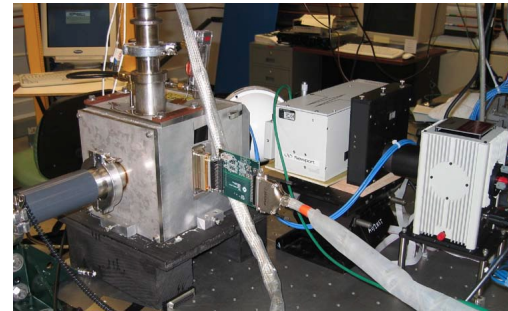
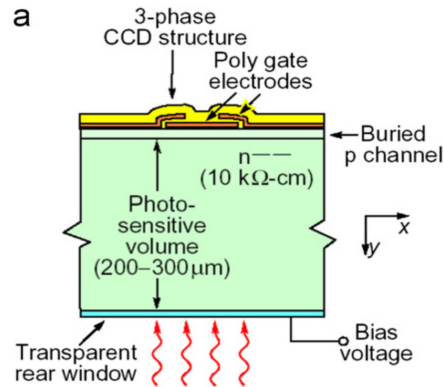
Gravity: 1 m ~ 102 neV  
Magnetic field: 1 T ~ 60 neV

# UCN Microscopy: using scintillators



W. Wei et al, NIMA 830 (2016) 36-43.

# UCN imaging: direct detection



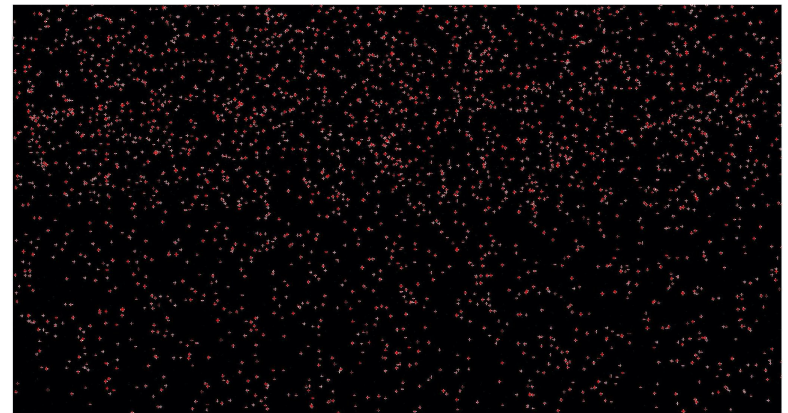
K. Kuk et al., UCN projection imaging (2021)

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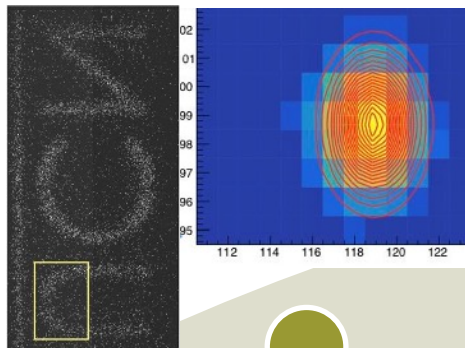
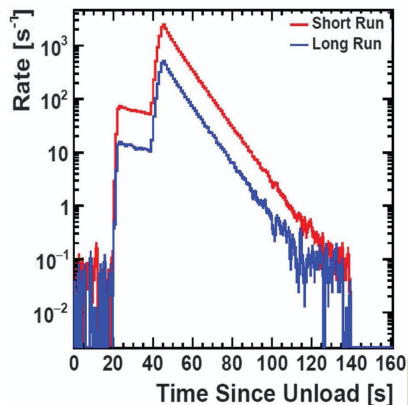
# Compact UCN camera



*(without scintillator or  
other neutron converters)*



# Advances in higher resolution: $\sim 1 \mu\text{m}$



2020

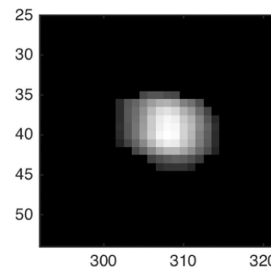
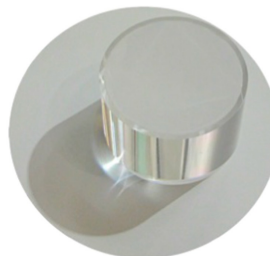
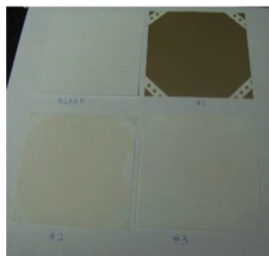
2019

2018

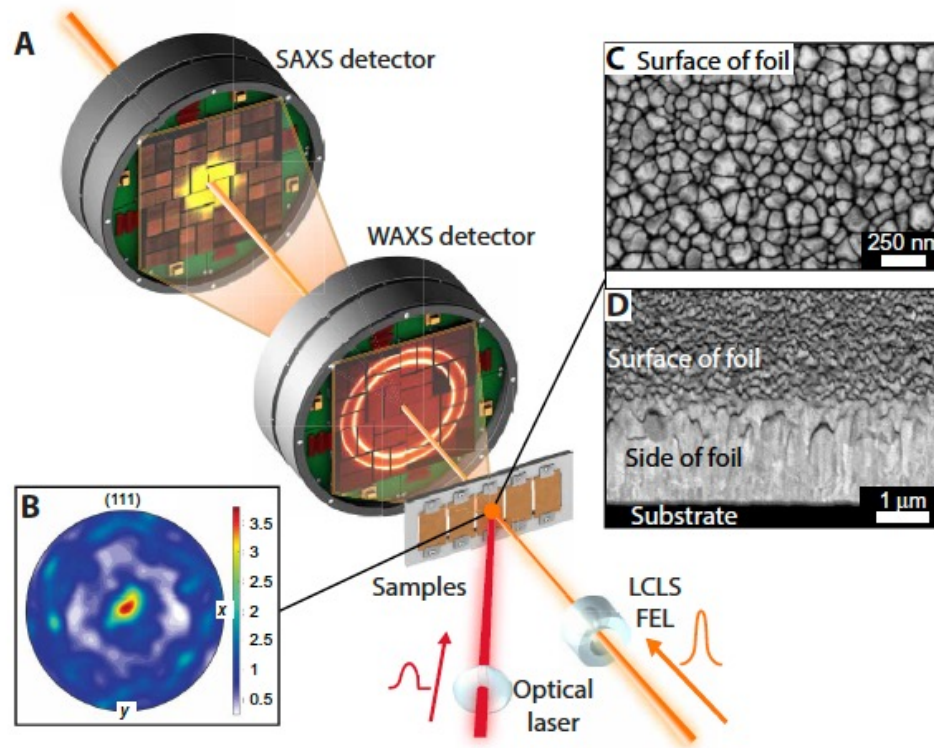
Pattie et al, *Science* **360** (2018)

2015

• 2016

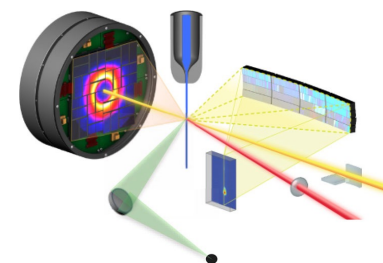


# Femto-sec SAXS/WAXS at LCLS



Coakley *et al.* (2020)

- $\sim 100$  fs
- $\lambda \sim 0.15$  nm
- $1\text{--}30 \times 10^{12}$  ph/pulse
- 120 Hz



Kunnus *et al.* (2020)

# TR-SANS, TI-SANE, etc.

Thermal or cold  $\lambda_t \sim 0.18$  nm

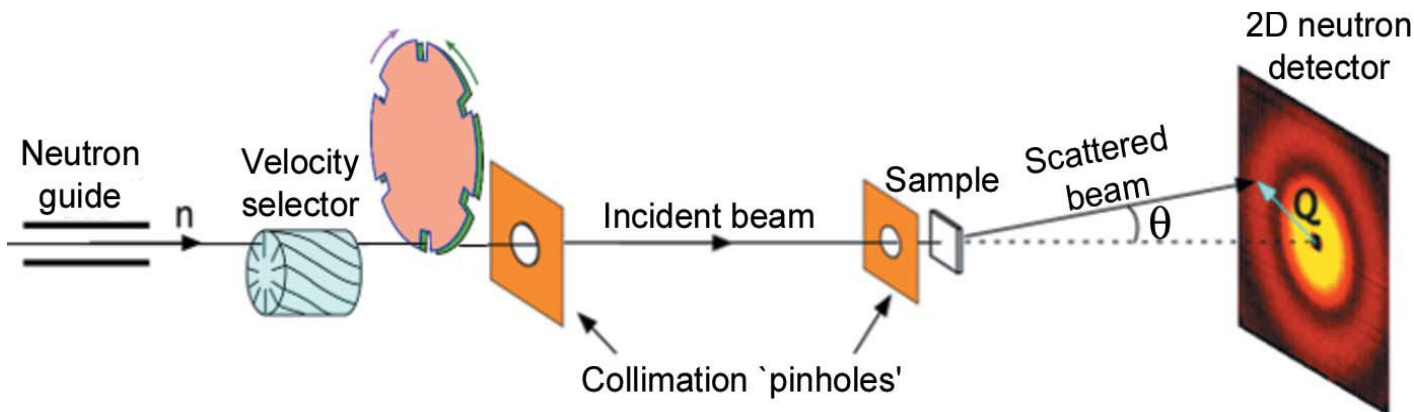
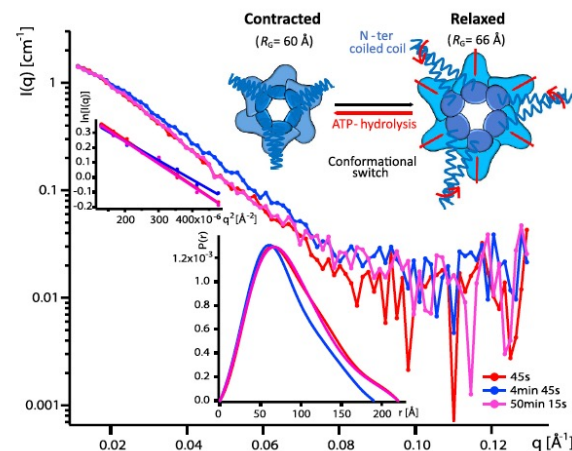
## ■ TISANE

- Gahler & Golub (1999)
- $\mu$ s [Wiedenmann:2006, Kipping:2008]
- Sub-ms scale [Glinka: 2020]

## ■ Hours to ms [Isnard:2007]

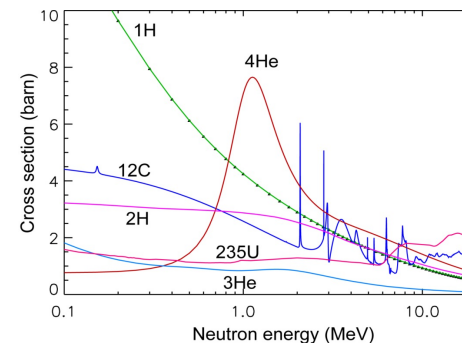
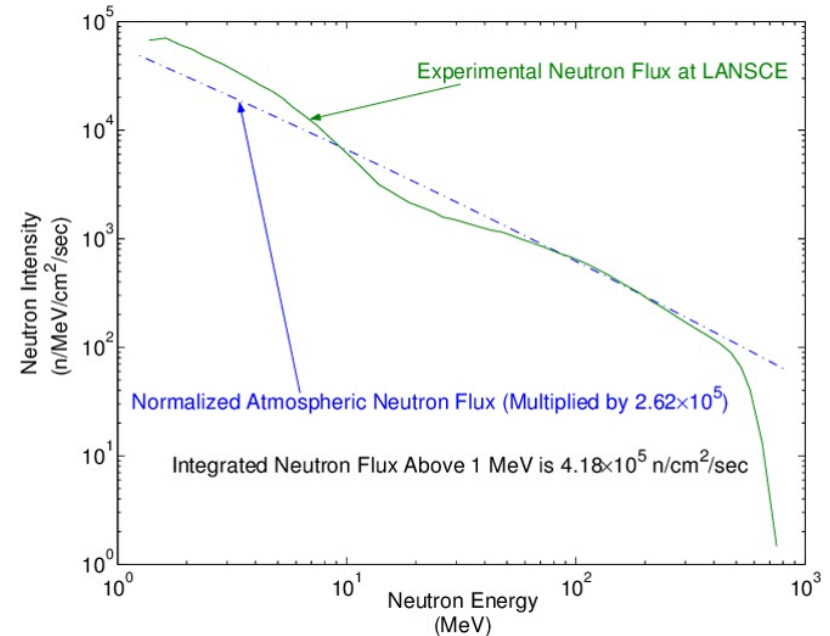
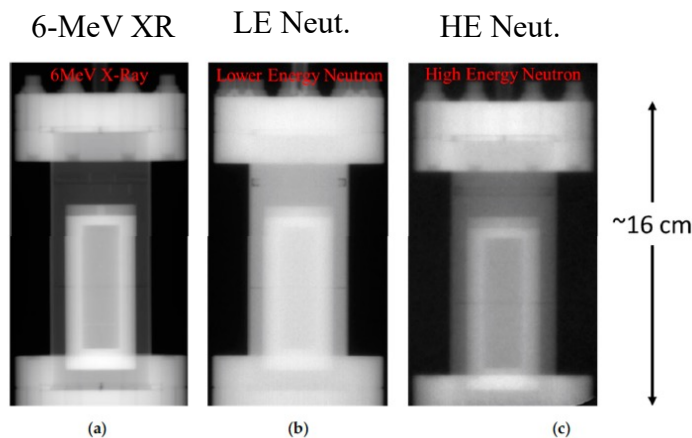
## ■ TR-SANS [Nakano:2009]

## ■ Sub-minute scale [Ibrahim: 2017]



# SIFaN: Motivation [High-energy neutron radiography]

- **White neutron spectrum**
  - 0.6 – 400 MeV (4FP-60R)
  - Every neutron counts
- **$2 \times 10^6$  n/cm<sup>2</sup>/s**
- **~ 30 cm x 20 cm**
- **Small. Cross sections**



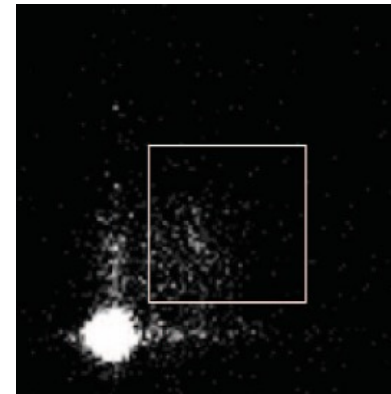
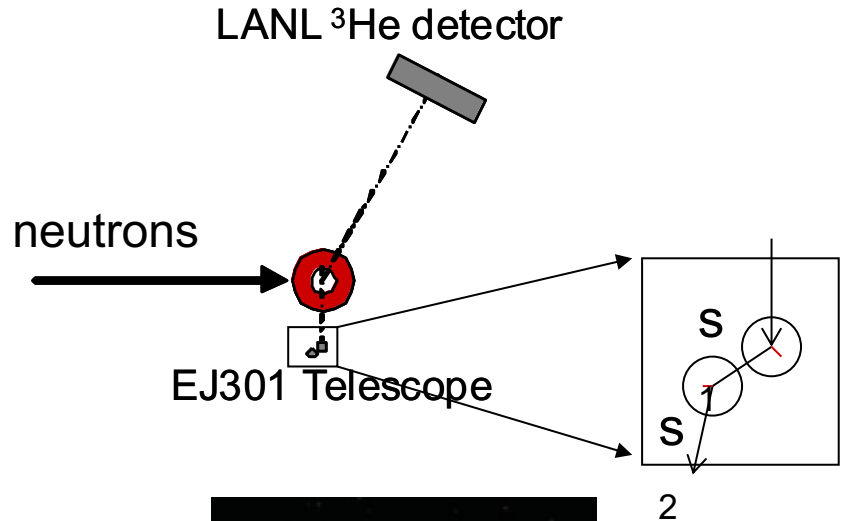
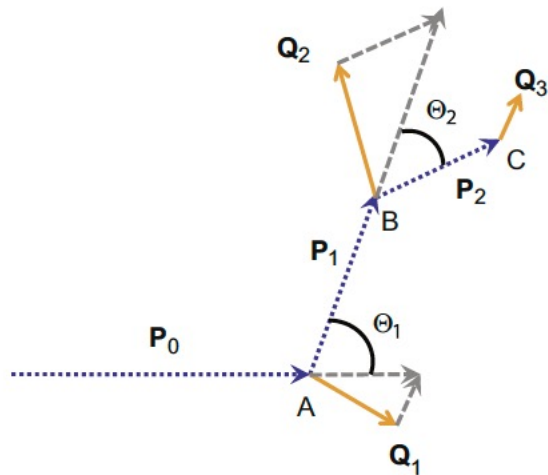
Nelson *et al* (2018).

UNCLASSIFIED

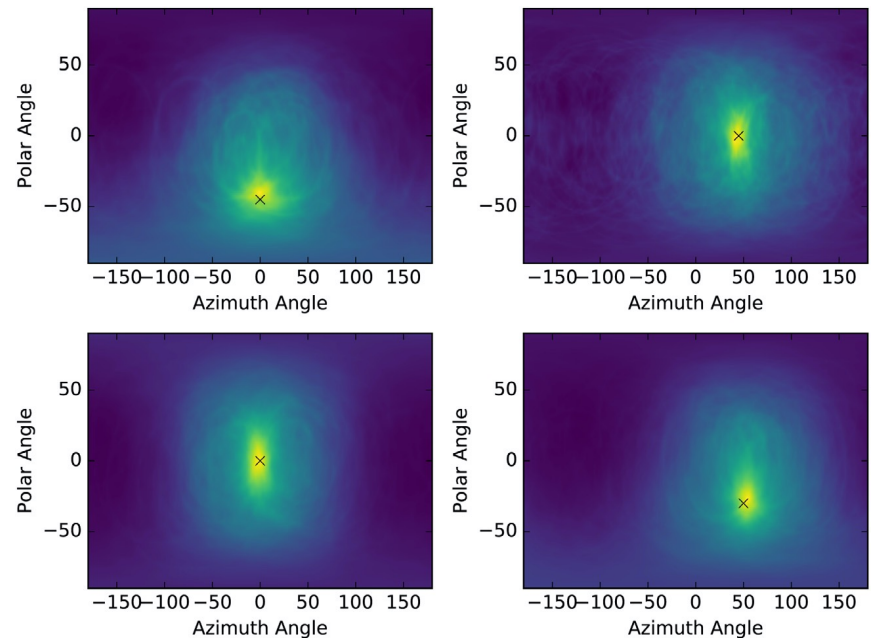
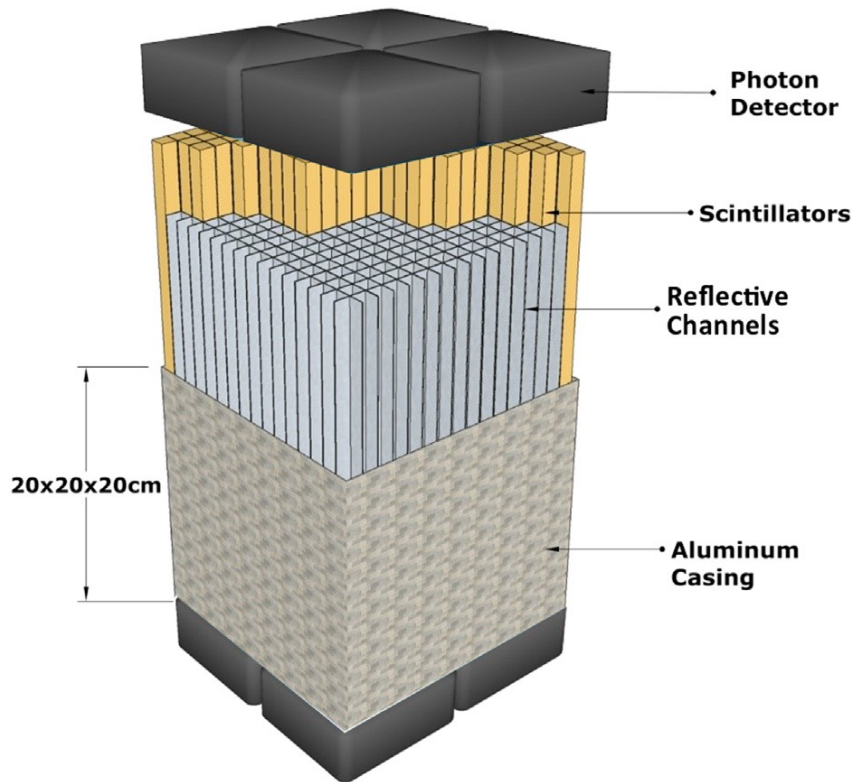
BoD DEC 2014

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# SIFaN: Fast neutron telescope



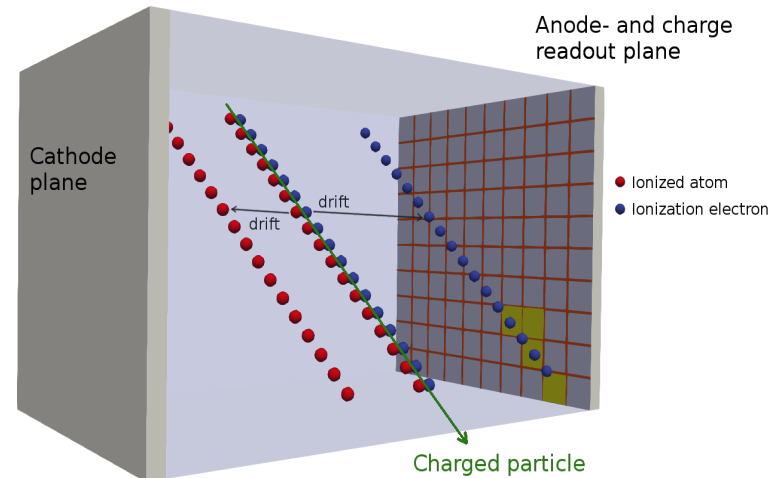
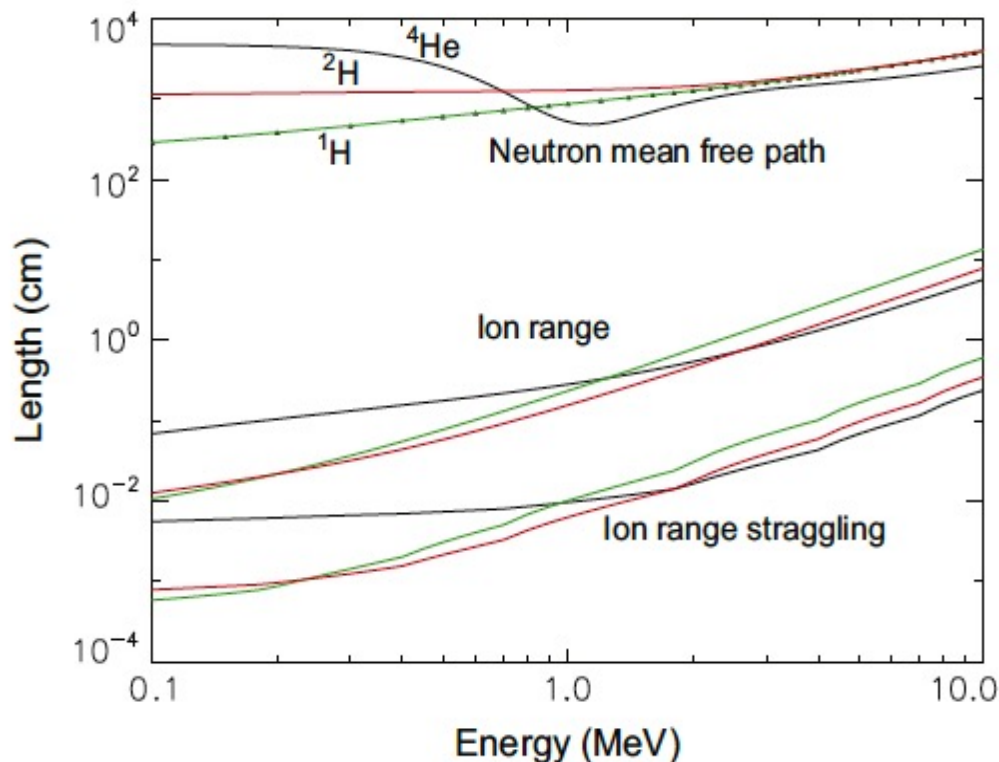
# SIFaN: ~ medium resolution



Weinfurther et al., 2018

# SIFaN: High resolution (TPC design & materials)

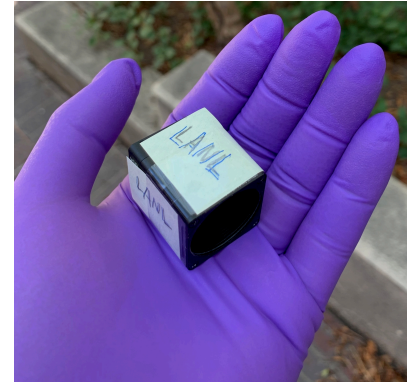
$P \sim 10$  bar



<https://argoncube.org/LArTPCs.html>

# Summary

- **Thermal neutron detection based on  $^{10}\text{B}$** 
  - Architectural innovations
- **UCN: One of the world's smallest neutron cameras demonstrated**
  - UCN QIS
- **SIFaN: HE/Fast Neutron radiography**
  - Fast neutron tracking & imaging



# Acknowledgement

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- **UCN $\tau$  collaboration**

(All LANL except specified explicitly)

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